

FLASHOVER PERFORMANCE OF LIGHTNING PROTECTED BUILDINGS
USING SCALED MODELS AND ELECTRIC FIELD ANALYSIS

IRSHAD ULLAH

A thesis submitted in
fulfillment of the requirement for the award of the
Doctor of Philosophy of Electrical Engineering



Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

JUNE 2018

To my parents, family and friends for their endless and constant prayers and moral support



ACKNOWLEDGEMENT

First and foremost, I pray to almighty ALLAH for His Kindness and Blessing throughout my journey in completing this work.

I like to express my sincere gratitude to my academic supervisors Dr. Md. Nor Ramdon Bin Baharom and Prof Dr. Hussein Ahmad for their tremendous constant guidance, contribution of high technical knowledge, encouragements, advice, great effort, patience and understanding throughout ensuring the success in my research and work in this project.

This Ph.D. work has been made possible with the financial support from the ORICC, University Tun Hussein Onn Malaysia (UTHM) and with the moral support of the Faculty of Electrical and Electronic Engineering (FKEE). I would like to present my gratitude to the staff of the ORICC and FKEE who have been involving with us during this project.

I also want to thank my parents for their moral support, encouragement and endless prayers. Furthermore, I would like to thank my wife for her great support, prayers and selfless love throughout ensuring the success of the study.

Lastly, I offer my regards and blessing to all those who supported me in any respect during completion of the project.

ABSTRACT

In early era, Benjamin Franklin discovered that the application of Lightning Rod (also known as the Franklin Rod) method is found to be effectived as a lightning protective device for buildings. Hence, it was considered among the best solution to overcome the problems facing by publics due to lightning strikes. However, few years later it was found that the corroded Franklin Rod due to the impact of environmental contaminations tends to reduce its ability to effectively capture the lightning strikes. The directly or indirectly impacts of lightning strikes had caused owners to spend huge amount of money just to repair damages on the buildings. Nowadays, there were many professional standards and documents guiding public to properly install the building's lightning protection system, yet the same damages problems had shown to be frequently occur that related to the strikes often bypasses the of Lightning Air Terminal (LAT) system. The main reason for this could be due to lacking ideas by learned circle of lightning experts as not to fully understand the behavior of Franklin Rods system when it interacts with the lightning leaders. Therefore, this thesis discusses the works that investigated the flashover performances occurred on the buildings with various structural geometry shapes. The case study method is using small scaled models for both laboratory and simulation works, aiming to understand the Franklin Rods performance on capturing lightning leaders. Summarizing the works, about 11 scaled-down building shape models equipped with Franklin Rods system are selected in the case studies such as follows; a conical, gable, triangular, half circle, L-shape, square, cylindrical, butterfly, pyramid, rectangular and inclined like shapes. These models were then injected with 30 lightning flashes each using the 100 kV_{peak} single stage impulse generator. This number of flashes is considered as total two-years lightning activity frequencies in Malaysia, which the lighting flash density is statistically recorded to be around 15 flashes / year / km². The maximum applied voltage is about 86.5 kV_{peak}. The model scaling concept is based on 1:30 cm ratio for every 3 m height of building structure. Interestingly, the overall work data had shown that the pyramid-like shapes is found

to be the best structure type to be used in reducing the LAT bypasses and direct strike damages. The structure's Franklin Rod protection system captured the least number of strikes during competitive tests conducted on all of the scaled down building models. Works of electric field analysis on all building models were conducted using ANSYS Maxwell simulation tool. Utilisation of electric field plot data in this work enables the creation of likelihood factor (ranging from 0.1 to 0.9) method that so useful to capable predict the strikes pattern occurring on dedicated terminal rod. Both laboratory and simulation work also confirm that the edge shapes play crucial roles as intense electric fields is found to accumulate on the edges area when the Franklin Rod intercepts the lightning leaders. These mentioned findings lead to introducing better method of LAT placement on the top of the building, whereby the existing lightning protection system is recommended to have one of installed LAT rods elongated to act as sacrificial point to directly attract lightning strikes. All the work and key findings in this work can contribute to the science and technology field toward having a better LAT lightning protection system and also lead to better decision in selecting / designing the shapes and edges concept as to reduce likelihood of LAT bypasses and damages of the building structure.



ABSTRAK

Pada era awal, Benjamin Franklin mendapati bahawa penggunaan Rod Pemimpin Kilat (juga dikenali sebagai *Rod Franklin*) didapati berkesan sebagai alat pelindung kilat untuk bangunan. Oleh itu, ia dianggap antara penyelesaian terbaik untuk mengatasi masalah yang dihadapi oleh orang awam disebabkan pancaran kilat. Walaubagaimanapun, beberapa tahun kemudian didapati bahawa Franklin Rod yang berkarat akibat kesan pencemaran alam sekitar cenderung untuk mengurangkan keupayaannya untuk menangkap serangan kilat dengan efektif. Kesan langsung atau tidak langsung serangan kilat telah menyebabkan pemilik menghabiskan sejumlah besar wang hanya untuk membaiki kerosakan di bangunan. Pada masa kini, terdapat banyak piawaian profesional dan dokumen yang membimbing orang ramai untuk memasang sistem perlindungan kilat bangunan dengan betul, namun masalah kerosakan yang sama telah ditunjukkan sering berlaku yang berkaitan dengan serangan kilat yang sering melepasi sistem *Lightning Air Terminal (LAT)*. Punca utama mungkin disebabkan oleh kekurangan idea di kalangan ahli penyelidik fenomena kilat yang tidak memahami sepenuhnya kelakuan sistem Franklin Rods apabila ia berinteraksi dengan pemimpin kilat. Oleh itu, tesis ini membincangkan kerja-kerja yang menyiasat persembahan *flashover* berlaku di bangunan dengan pelbagai bentuk geometri struktural. Kaedah kajian kes menggunakan model skala kecil untuk kedua-dua kerja makmal dan simulasi, bertujuan untuk memahami prestasi *Franklin Rods* dalam menangkap pancaran kilat. Merumuskan kerja, kira-kira 11 model bentuk bangunan berskala kecil pelbagai bentuk yang dilengkapi dengan sistem *Franklin Rods* dipilih dalam kajian kes seperti berikut; lingkaran kon, gable, segitiga, setengah bulatan, bentuk L, persegi, silinder, rama-rama, piramid, segi empat tepat dan bentuk cenderung. Kemudian model-model ini setiap satunya direnjat dengan 30 pancaran kilat menggunakan $100 \text{ kV}_{\text{puncak}}$. Jumlah renjatan ini dianggap sebagai kekerapan aktiviti kilat selama dua tahun di Malaysia, yang ketumpatan kilat cahaya dicatatkan secara statistik berada sekitar 15 pancaran / setahun / km^2 . Voltan maxima yang digunakan adalah pada kadaran $86.5 \text{ kV}_{\text{puncak}}$.

Konsep pengecilan skala model berdasarkan nisbah 1:30 cm untuk ketinggian struktur 3 m setiap bangunan. Menariknya, data kerja keseluruhan menunjukkan bahawa bentuk seperti piramid merupakan struktur terbaik yang boleh digunakan untuk mengurangkan pintasan *LAT* dan kerosakan langsung pada permukaan bangunan. Struktur bentuk ini membolehkan sistem perlindungan *Franklin Rod* menangkap paling sedikit jumlah pancaran semasa ujian persaingan yang dilakukan pada semua model bangunan berskala rendah. Kerja-kerja analisis medan elektrik pada semua model bangunan telah dijalankan menggunakan alat simulasi *ANSYS Maxwell*. Pemanfaatan data plot medan elektrik dalam kerja kami membolehkan penciptaan kaedah faktor kemungkinan (dari 0.1 hingga 0.9) yang amat berguna digunakan untuk meramalkan corak pancaran yang berlaku pada rod terminal khusus. Kerja-kerja makmal dan simulasi juga mengesahkan bahawa bentuk pinggir pada sesebuah struktur bangunan memainkan peranan penting di mana medan elektrik yang kuat dijumpai berkumpul di kawasan pinggir struktur bahan apabila *Franklin Rod* memintas cahaya kilat utama. Penemuan-penemuan yang disebutkan di atas membawa kepada kaedah penempatan *LAT* yang lebih baik di bahagian atas bangunan, di mana sistem perlindungan petir sedia ada disyorkan untuk mempunyai satu rod *LAT* yang dipasangkan lebih panjang untuk bertindak sebagai punca utama bagi menarik perhatian pancaran kilat. Semua kerja dan penemuan penting dalam kerja ini boleh menyumbang kepada bidang sains dan teknologi ke arah mempunyai sistem perlindungan kilat *LAT* yang lebih baik dan juga membawa kepada keputusan yang lebih baik dalam memilih / merekabentuk konsep bentuk dan pinggir objek bagi mengurangkan kemungkinan perlepasan jangkauan *LAT* dan kerosakan pada struktur bangunan.

TABLE OF CONTENTS

DECLARATION	ii
DEDICATION	iii
ACKNOWLEDGEMENT	iv
ABSTRACT	v
ABSTRAK	vii
TABLE OF CONTENTS	ix
LIST OF TABLES	xv
LIST OF FIGURES	xvii
LIST OF SYMBOLS AND ABBREVIATIONS	xxix
CHAPTER 1 INTRODUCTION	1
1.1 Research background	1
1.2 Problem statement	4
1.3 Objectives of the research study	7
1.4 Scope of the study	8
1.5 Research contributions	9
1.6 Thesis organization	9
CHAPTER 2 LITERATURE REVIEW	12
2.1 Pattern of lightning strike points on geometrical shapes	12
2.1.1 Lightning and building structures	15
2.1.2 Lightning strikes on Putrajaya Minaret	17
2.1.3 Guangzhou IFC and new TV tower China	18
2.1.4 Lightning attachment to CN Tower Canada	19
2.1.5 Peissenberg Tower, Germany	20
2.1.6 Lightning strikes on small building structures	20
2.1.7 Lightning protection and scaled objects	22
2.1.8 Lightning fatalities in different countries	23
2.1.9 Lightning fatalities in the USA	24

2.1.10	Lightning fatalities in the UK	25
2.1.11	Lightning fatalities in China	26
2.1.12	Lightning fatalities in South Asia	27
2.1.13	Lightning fatalities in Swaziland and Greece	28
2.1.14	Lightning fatalities in Malaysia	28
2.1.15	Lightning fatalities per continent	29
2.1.16	LAT capturing capability and electric field generation	30
2.1.17	Placement of LAT on a building structure	32
2.1.18	Electric field propagation on the LAT and inside the buildings	34
2.2	Upward streamers and likelihood of the lightning strikes	36
2.2.1	Likelihood of lightning strike and the hazard identification	38
2.2.2	Lightning air terminal bypasses	40
2.3	Lightning protection standards and methods of protection	42
2.3.1	Rolling Sphere Method (RSM)	42
2.3.2	Ionization Surface Method (ISM)	46
2.4	Chapter summary	48
CHAPTER 3	METHODOLOGY	49
3.1	Overall methodology of the research	49
3.2	Phase 1: Experimental process	51
3.2.1	Equipment setup	51
3.2.2	Model development	53
3.2.3	Development of the intermediate (model no.2)	56
3.2.4	Final experimental model no.3	59
3.2.5	Profiling structure selection and fabrication	64
3.3	Phase 2: Simulation process	69
3.4	Phase 3: Modified protection system	71
3.5	Efficacy of research methods	72
3.6	Chapter summary	73
CHAPTER 4	EXPERIMENTAL RESULTS	74

4.1	Overview of the experimental work	74
4.1.1	DC and impulse calibration test	76
4.2	Experimental results	77
4.2.1	Lightning strike distribution on conical shape	77
4.2.2	Lightning strike distribution on gable shape	78
4.2.3	Lightning strike distribution on triangular shape	80
4.2.4	Lightning strike distribution on half circle/arced shape	82
4.2.5	Lightning strike distribution on L-shape	84
4.2.6	Lightning strike distribution on square shape	86
4.2.7	Lightning strike distribution on cylindrical shape	88
4.2.8	Lightning strike distribution on butterfly shape	90
4.2.9	Lightning strike distribution on pyramid shape	92
4.2.10	Lightning strike distribution on rectangular shape	94
4.2.11	Lightning strike distribution on inclined shape	96
4.3	Competition test for better structure selection as lightning protection	98
4.4	Modified building protection system	104
4.4.1	Modified protection system for gable shape	105
4.4.2	Modified protection system for triangular shape	106
4.4.3	Modified protection system for half circle/arc shape	107
4.4.4	Modified protection system for L- shape	108
4.4.5	Modified protection system for square shape	108
4.4.6	Modified protection system for cylindrical shape	109
4.4.7	Modified protection system for butterfly shape	110
4.4.8	Modified protection system for rectangular shape	111
4.4.9	Modified protection system for inclined shape	111
4.5	Comparison with previous research	112
4.6	Working mechanism of the experimental work	113

4.7	Chapter summary	118
CHAPTER 5	SIMULATION RESULTS	119
5.1	Simulation overview	119
5.1.1	Electric field simulation on different air terminal	120
5.1.2	Electric field intensity on 3-D model of conical shape	121
5.1.3	Electric field intensity on 3-D model of gable shape	123
5.1.4	Electric field intensity on 3-D model of triangular shape	124
5.1.5	Electric field intensity on 3-D model of half circle/arc shape	127
5.1.6	Electric field intensity on 3-D model of L-shape shape	129
5.1.7	Electric field intensity on 3-D model of square shape	131
5.1.8	Electric field intensity on 3-D model of cylindrical shape	133
5.1.9	Electric field intensity on 3-D model of butterfly shape	135
5.1.10	Electric field intensity on 3-D model of pyramid shape	137
5.1.11	Electric field intensity on 3-D model of rectangular shape	139
5.1.12	Electric field intensity on 3-D model of inclined shape	141
5.2	Upward leader inception and the likelihood of lightning strikes on LATs	142
5.2.1	Likelihood of lightning strikes on conical shape with and without upward leaders	145
5.2.2	Likelihood of lightning strikes on gable shape with and without upward leaders	148



5.2.3	Likelihood of lightning strikes on triangular shape with and without upward leaders	150
5.2.4	Likelihood of lightning strikes on half circle/arc shape with and without upward leaders	153
5.2.5	Likelihood of lightning strikes on L-shape with and without upward leaders	155
5.2.6	Likelihood of lightning strikes on square shape with and without upward leaders	157
5.2.7	Likelihood of lightning strikes on cylindrical shape with and without upward leaders	160
5.2.8	Likelihood of lightning strikes on butterfly shape with and without upward leaders	162
5.2.9	Likelihood of lightning strikes on pyramid shape with and without upward leaders	164
5.2.10	Likelihood of lightning strikes on rectangular shape with and without upward leaders	167
5.2.11	Likelihood of lightning strikes on inclined shape with and without upward leaders	170
5.3	Lightning air terminal bypasses	172
5.3.1	Lightning air terminal bypasses on rectangular shape	172
5.3.2	Lightning air terminal bypasses on butterfly shape	173
5.4	Electric field simulations of modified building protection system	174
5.4.1	Modified protection system for gable shape	174
5.4.2	Modified protection system for triangular shape	176
5.4.3	Modified protection system for half circle/arc shape	177
5.4.4	Modified protection system for L- shape	178
5.4.5	Modified protection system for square shape	179
5.4.6	Modified protection system for cylindrical shape	180
5.4.7	Modified protection system for butterfly shape	181



5.4.8	Modified protection system for rectangular shape	182
5.4.9	Modified protection system for inclined shape	183
5.5	Discussion on ever all simulation process	187
5.6	Chapter summary	190
CHAPTER 6	CONCLUSION AND FUTURE WORK	191
6.1	Conclusion	191
6.2	Research limitations	193
6.2.1	In-door testing versus outdoor experiment	193
6.2.2	Lightning flash photography	193
6.2.3	Real condition and natural materials	194
6.2.4	Simulation	194
6.3	Future work	195
	REFERENCES	196
	LIST OF PUBLICATIONS	206
	VITA	208



LIST OF TABLES

2.1	Lightning fatalities in different continents of the world	30
2.2	Breakdown voltage and E.field of the CAT and BCAT	35
2.3	Review table of the previous research work.	47
3.1	Initial model development of model no.1.	54
3.2	Dimensions of the equipment	56
3.3	Dimensions of the final model	60
3.4	Comparative table of model fabrication	63
4.1	D C and impulse calibration test readings	76
4.2	Lightning attachment pattern on LATs installed on gable shape	80
4.3	Lightning attachment pattern on installed LATs of the triangular shape	82
4.4	Lightning attachment distribution installed LATs on half circle	84
4.5	Lightning attachment strike pattern on installed LATs of L-shape	86
4.6	Lightning attachment pattern on installed LATs of square shape	88
4.7	Lightning attachment pattern on installed LATs of cylindrical shape	90
4.8	Lightning attachment pattern on butterfly shape	92
4.9	Lightning attachment pattern on the installed LATs of pyramid shape	94
4.10	Lightning attachment pattern on the installed LATs of rectangular shape	96

4.11	Lightning attachment pattern on the installed LATs of inclined shape	98
4.12	Numbers of strikes on different shapes in first competition test.	99
4.13	Numbers of strikes on different shapes in second competition test	101
4.14	Numbers of strikes on different shape in third competition test	102
4.15	Number of strikes on different shape in fourth competition test.	104
5.1	Conical shape likelihood of lightning strike with and without upward leaders	147
5.2	Gable shape likelihood of lightning strikes with and without upward leaders	150
5.3	Triangular shape likelihood of lightning strike with and without upward leaders	152
5.4	Half circle/arc shape likelihood of lightning strike with and without upward steamers	155
5.5	L-shape likelihood of lightning strike with for upward leaders	157
5.6	Square shape likelihood of lightning strikes with and without upward leaders	159
5.7	Cylindrical shape likelihood of lightning strikes with and without upward leaders	162
5.8	Likelihood of lightning strikes with and without upward leaders	164
5.9	Likelihood of lightning strikes with and without upward leaders	166
5.10	Likelihood of lightning strikes with and without upward leaders	169
5.11	Likelihood of lightning strikes with and without upward leaders	171
5.12	Recommendation table for various building height	185

LIST OF FIGURES

1.1	Different types of LATs; (a) standard (b) concave (c) blunt (d) flat (e) conical	3
1.2	(a) possible lightning strike without LAT (b) possible lightning strikes with LAT	5
1.3	(a) LAT bypasses (b) close view	6
1.4	Lightning air terminal bypasses on Faber Towers	7
2.1	Lightning strike pattern on rectangular rooftops; (a) Villa Putra (b) Bank Industri (c) Faber Towers	13
2.2	Lightning damages on gable shape rooftops; (a) UTM building (b) residential house	14
2.3	Lightning strike points on cylindrical and conical shape; (a) cylindrical building (b) mosque in Putrajaya	14
2.4	Lightning strikes on Putra Mosque Minaret	17
2.5	Lightning attachment to a tall object in China; (a) towers height (b) lightning flash on IFC tower (c) to the TV tower	18
2.6	Lightning strike on CN tower Canada	19
2.7	Lightning attachment to the Peissenberg Tower Germany	20
2.8	Lightning strike on small structures in different countries; (a) Kasansama village Zambia (b) Chibombo, Zambia (c) Katuya, Zambia	21
2.9	lightning strike on similar small houses house ; (a) similar house struck by lightning in Namibia (b) Typical Ger in Mongolia	22
2.10	World Iso- keraunic level map	24

2.11	Deaths due to lightning fires in US and UK	25
2.12	Arm burned due to lightning in 2008 in the UK	26
2.13	Number of fatalities in China per million since 1197-2010	27
2.14	A victim injured in Bangladesh due to lightning	28
2.15	Age of the people victims of lightning	29
2.16	Competition test for different LAT tips (a) standard tip (b) concave (c) flat (d) conical	31
2.17	Incorrect LAT installation (a) wrong LAT installation on a house (b) wrong LAT installation on a college	33
2.18	Magnetic field distribution due to lightning inside building	35
2.19	Connection between downward and upward leader	37
2.20	Bypasses on technology park Malaysia	40
2.21	Bypasses on buildings structures (a) small bypass on public building (b) bypass on the top of a firewall	41
2.22	Single mast protection method	43
2.23	Two masts protection method	44
2.24	Three masts protection	45
2.25	Four masts protection method	45
3.1	Overall methodology of the work	50
3.2	Schematic diagram of the experimental setup	51
3.3	Block diagram of the impulse generator	52
3.4	High voltage impulse generator arrangement	52
3.5	Initial model development; (a) building model no.1 (b) top electrode (c) engineering drawing of the experimental work (d) flashover breakdown	55
3.6	Experimental arrangement of the enhanced model; (a) test object/ square shape (b) top electrode (c) engineering drawing (d) lightning attachment to T1 (e) lightning attachment to T2 (f) lightning attachment to T4	58
3.7	Experimental arrangement and final model; (a) square building structure installed with 4 LATs (b)	

top electrode (c) engineering drawing of the experimental setup (d) Lightning flash on T1 (e) lightning flash on T2 (f) lightning flash on T3 (g) lightning flash on T4	62
3.8 Geometrical shape with different lightning air terminal arrangement; (a) square shape (b) rectangular (c) gable shape (d) cylindrical (e) half circle shape (f) L- shape (g) triangular shape (h) inclined shape (i) butterfly shape (j) pyramid shape (k) conical shape	68
3.9 Flow chart of model selection	69
3.10 Flowchart of the simulation process	71
3.11 Modified protections system	72
4.1 Devices used to measure STP; (a) 4 in 1 meter (b) barometer	75
4.2 Lightning flash on a conical shape	77
4.3 Lightning strike distribution on gable shape; (a) scaled gable shape (b) lightning strike on T1 (c) lightning strike on T2 (d) lightning strike on T3	79
4.4 Lightning strike distribution on triangular shape; (a) scaled triangular shape (b) lightning strike on T1 (c) lightning strike on T2 (d) lightning strike on T3	81
4.5 Lightning strike distribution on half circle shape; (a) scaled half circle shape (b) lightning strike on T1 (c) lightning strike on T2 (d) lightning strike on T3	83
4.6 Lightning strike distribution on L-shape; (a) scaled L-shape (b) lightning strike on T1 (c) lightning strike on T2 (d) lightning strike on T3	85
4.7 Lightning strike distribution on square shape; (a) scaled square shape (b) Lightning strike on T1 (c) lightning strike on T2 (d) lightning strike on T3 (e) lightning strike on T4	87
4.8 Lightning strike distribution on circular shape; (a) scaled circular shape (b) Lightning strike on T1 (c)	

	lightning strike on T2 (d) lightning strike on T3 (e) lightning strike on T4.	89
4.9	Lightning strike distribution on butterfly shape; (a) scaled butterfly shape (b) Lightning on T1 (c) lightning on T2 (d) lightning on T3 (e) lightning on T4	91
4.10	Lightning strike distribution on hexagonal shape; (a) scaled hexagonal shape (b) lightning strike on T1	93
4.11	Lightning strike distribution on hexagonal shape; (a) scaled hexagonal shape (b) lightning strike on T1 (c) lightning strike on T2 (d) lightning strike on T3 (e) lightning strike on T4 (f) lightning strike on T5 (g) lightning strike on T6	95
4.12	Lightning strike distribution on inclined shape; (a) scaled inclined shape (b) lightning strike on T1 (c) lightning strike on T2	97
4.13	First competition test for circular, inclined, rectangular and square shape; (a) Lightning strike on circular shape (b) lightning strike on the inclined shape (c) lightning strike on rectangular shape (d) lightning strike on square shape	100
4.14	Second competition test for gable, half circle, L- shape and triangular; (a) Lightning strike on gable shape (b) lightning strike on half circle shape (c) lightning strike on half circle shape (d) lightning strike on L- shape (e) lightning strike on L-shape (f) strike on triangular shape	101
4.15	Third competition test for butterfly, cylindrical and hexagonal shape; (a) Lightning strike on butterfly shape (b) lightning strike on the cylindrical shape (c) lightning strike on pyramid shape	102
4.16	Fourth competition tests for hexagonal, inclined and triangular shape; (a) Lightning strike on hexagonal	

	shape (b) lightning strike on inclined shape (c) lightning strike on a triangular shape	103
4.17	Modified protection method for gable shape; (a) Gable shape with elongated air terminal (b) lightning flash on the elongated air terminal	106
4.18	Modified protection method for triangular shape (a) triangular shape with elongated air terminal (b) lightning flash on the elongated air terminal	106
4.19	Modified protection method for half circle/arc shape; (a) half circle/arc shape with elongated air terminal (b) lightning flash on the elongated air	107
4.20	Modified protection method for L- shape; (a) L-shape with elongated air terminal (b) lightning flash on the elongated air terminal	108
4.21	Modified protection method for square shape; (a) square shape with elongated air terminal (b) lightning flash on the elongated air terminal	109
4.22	Modified protection method for circular shape; (a) circular shape with elongated air terminal (b) lightning flash on the elongated air terminal	109
4.23	Modified protection method for butterfly shape; (a) butterfly shape with elongated air terminal (b) lightning flash on the elongated air terminal	110
4.24	Modified protection method for rectangular shape; (a) rectangular shape with elongated air terminal (b) lightning flash on the elongated air terminal	111
4.25	Modified protection method for inclined shape; (a) inclined shape with elongated air terminal (b) lightning flash on the elongated air terminal	112
4.26	Electrification of grounded building structure installed with LAT during thunderstorm; (a) matured cumulonimbus cloud b) cloud-to-ground electric field concentration (c) The mirror-image positive charges due to cloud base negative charges, the	

	grounded structure covered with positive charges (d) electric field lines linking the ground and building with electric fields connected to the cloud	116
4.27	Electrification of grounded building structure installed with LAT during a thunderstorm; (a) electric field analysis of the protected building with domain defined (b) the mirror image positive charges encompassing the protected building	117
4.28	Electrification of grounded building structure installed with LAT during thunderstorm (a) The upper part of building with charge distribution of positive charges (b) The upper building sectionalized for electric field analysis (c) electric field lines linking the ground and building with ground to cloud electric fields (symmetrical consideration) with upward and downward streamer involve	117
5.1	Electric field plot for 3-D conical shape; (a) conical shape 3-D model (b) field plot of the standard situations (c) field plot of the laboratory conditions	122
5.2	Graphical representation of the field plot for 3-D conical shape; (a) electric field value in x and y-axis for standard conditions (b) electric field value for experimental condition in x and y-axis.	122
5.3	Electric field plot for 3-D gale shape; (a) gable shape 3-D model (b) field plot of the standard situations (c) field plot of the laboratory conditions	123
5.4	Graphical representation field plot for 3-D gable shape; (a) electric field value in x and y-axis for standard conditions (b) electric field value for the experimental condition in x and y-axis	124
5.5	Electric field plot for 3-D triangular shape; (a) triangular shape 3-D model (b) field plot of the	

	standard situations (c) field plot of the laboratory conditions	125
5.6	Graphical representation field plot for 3-D triangular shape; (a) electric field value in x and y-axis for standard conditions (b) electric field value for the experimental condition in x and y-axis	126
5.7	Electric field plot for 3-D half circle shape; (a) half circle/arc shape 3-D model (b) field plot of the standard situations (c) field plot of the laboratory conditions	127
5.8	Graphical representation field plot for 3-D half circle/arc shape; (a) electric field value in x and y-axis for standard conditions (b) electric field value for the experimental condition in x and y-axis	128
5.9	Electric field plot for 3-D L- shape; (a) L- shape 3-D model (b) field plot of the standard situations (c) field plot of the laboratory conditions	129
5.10	Graphical representation of the field plot for 3-D L-shape; (a) electric field value in x and y-axis for standard conditions (b) electric field value for the experimental condition in x and y-axis	130
5.11	Electric field plot for 3-D square shape; (a) square shape 3-D model (b) field plot of the standard situations (c) field plot of the laboratory conditions	131
5.12	Graphical representation field plot for 3-D square shape; (a) electric field value in x and y-axis for standard conditions (b) electric field value for the experimental condition in x and y-axis	132
5.13	Electric field plot for 3-D cylindrical shape; (a) cylindrical shape 3-D model (b) field plot of the standard situations (c) field plot of the laboratory conditions	133
5.14	Graphical representation field plot for 3-D cylindrical shape; (a) electric field value in x and y-	

	axis for standard conditions (b) electric field value for the experimental condition in x and y-axis	134
5.15	Electric field plot for 3-D butterfly shape; (a) butterfly shape 3-D model (b) field plot of the standard situations (c) field plot of the laboratory conditions	135
5.16	Graphical representation field plot for 3-D butterfly shape; (a) electric field value in x and y-axis for standard conditions (b) electric field value for experimental condition in x and y-axis	136
5.17	Electric field plot for 3-D pyramid shape; (a) pyramid shape 3-D model (b) field plot of the standard situations (c) field plot of the laboratory conditions	137
5.18	Graphical representation field plot for 3-D pyramid shape; (a) electric field value in x and y-axis for standard conditions (b) electric field value for the experimental condition in x and y-axis	138
5.19	Electric field plot for 3-D rectangular shape; (a) rectangular shape 3-D model (b) field plot of the standard situations (c) field plot of the laboratory conditions	139
5.20	Graphical representation field plot for 3-D rectangular shape; (a) electric field value in x and y-axis for standard conditions (b) electric field value for the experimental condition in x and y-axis	140
5.21	Electric field plot for 3-D inclined shape; (a) inclined shape 3-D model (b) field plot of the standard situations (c) field plot of the laboratory conditions	141
5.22	Graphical representation of the field plot for 3-D inclined shape; (a) electric field value in x and y-axis for standard conditions (b) electric field value for the experimental condition in x and y-axis	142

5.23	Likelihood of lightning strike on conical shape with and without upward streamers initialization; (a) 3-D conical shape (b) electric field plot without upward streamers (c) electric field plot with upward streamer initialization	146
5.24	Maximum electric field value for conical shape; (a) maximum electric field without upward streamers (b) maximum electric field with upward streamers	147
5.25	Likelihood of lightning strike on gable shape with and without upward streamers; (a) 3-D gable shape (b) electric field plot without upward streamers (c) electric field plot with upward streamer initialization	149
5.26	Maximum electric field value for gable shape; (a) maximum electric field without upward streamers (b) maximum electric field with upward streamers	149
5.27	Likelihood of lightning strike on triangular shape with and without upward streamers; (a) 3-D triangular shape (b) electric field plot without upward streamers (c) electric field plot with an upward streamer	151
5.28	Maximum electric field value for triangular shape; (a) maximum electric field without upward streamers (b) maximum electric field with upward streamers	152
5.29	Likelihood of lightning strike on half circle/arc shape with and without upward streamers; (a) 3-D half circle/arc shape (b) electric field plot without upward streamers (c) electric field plot with upward streamer initialization	153
5.30	maximum electric field value for half circle/Arc shape; (a) maximum electric field without upward streamers (b) maximum electric field with upward streamers	154

REFERENCES

- [1] H. J. Christian, "Global Frequency and Distribution of Lightning as Observed from Space by the Optical Transient Detector," *J. Geophys. Res.*, vol. 108, no. 1, pp. 1–14, 2003.
- [2] D. J. B. and S. J. Goodman, "Regional Differences in Tropical Lightning Distributions," *J. Appl. Meteorol.*, vol. 39, no. 6, pp. 2231–2248, 2000.
- [3] M. Szczerbinski, "A discussion of Faraday Cage Lightning Protection and Application to Real Building Structures," *J. Electrostat.*, vol. 48, no. 3, pp. 145–154, 2000.
- [4] M. O. K. Gatewood and R. D. Zane, "Lightning Injuries," *Emergency Medicine Clinic of North America*, vol. 22, pp. 369–403, 2004.
- [5] J. Lu, H. Zhang, L. Yang, B. Li, Z. Fang, and X. Xu, "Forecast Method of Lightning Activity Based on the Weather Conditions," in *7th Asia-Pacific International Conference on Lightning, November, Chengdu, China*, 2011, pp. 625–628.
- [6] N. R. Misbah, M. Z. A. Ab Kadir, and C. Gomes, "Modelling and Analysis of Different Aspect of Mechanisms in Lightning Injury," in *4th International Conference on Modeling, Simulation and Applied Optimization, ICMSAO*, 2011, pp. 1–5.
- [7] O. Pinto, I. R. C. A. Pinto, and K. P. Naccarato, "Maximum Cloud-to-Ground Lightning Flash Densities Observed by Lightning Location Systems in the Tropical Region: A Review," *Atmos. Res.*, vol. 84, no. 3, pp. 189–200, 2007.
- [8] A. Weijun Li, Longyi Shao, Zongbo Shi, Jianmin Chen, Lingxiao Yang, QiYuan, Chao Yan, Xiaoye Zhang, Yaqiang Wang, Junying Sun, Yangmei Zhang, Xiaojing Shen, Zifa Wang, "On the Percentage of Lightning Flashes that Begin with Initial Breakdown Pulses," *J. Geophys. Res. Atmos. Res.*, vol. 119, no. 6, pp. 341–361, 2014.
- [9] K. Zafren, B. Durrer, J. P. Herry, and H. Brugger, "Lightning injuries: Prevention and on-site treatment in mountains and remote areas: Official

guidelines of the International Commission for Mountain Emergency Medicine and the Medical Commission of the International Mountaineering and Climbing Federation,” 2005.

- [10] “IEEE Guide for Direct Lightning Stroke Shielding of Substations,” 2013.
- [11] “IEEE Guide for the Application of Surge-Protective Components in Surge Protective Devices and Equipment Ports,” 2016.
- [12] D. W. Zipse, “Lightning Protection Methods: an Update and a Discredited System Vindicated,” *IEEE Trans. Ind. Appl.*, vol. 37, no. 2, pp. 407–414, 2001.
- [13] Y. S. Jin Lejun, Ganwen Lu, Jian Mie, Lu Han, “Research on the Characteristics for the Dielectric of Building and the Material of Grounding by Lightning Stroke,” in *Proceedings of the 9th International Conference on Properties and Applications of Dielectric Materials*, 2009, pp. 172–175.
- [14] Hughes J.F, *Understanding Lightning and Lightning Protection*, 1st ed. Budapest University of Technolingu and Economics: John Wiley & Sons, 2006.
- [15] E. P. Krider, “Benjamin Franklin and the First Lightning Conductors,” in *Proceedings of the International Commission on History of Meteorology*, 2004, vol. 1, pp. 1–13.
- [16] D. Zipse and G. Author, “Advancement of Lightning Protection and Prevention in the 20th Century,” *IEEE Industrial application society*, no. November, pp. 12–15, 2008.
- [17] R. L. Holle, “Lghtning Caused Casualtied in and Near Dwellings and other Buildings,” in *21st International Lighnting Detection Conference*, 2010, pp. 1–19.
- [18] M. Abu *et al.*, “Study on the Effectiveness of Lightning Rod Tips in Capturing Lightning Leaders,” *Electr. Eng.*, vol. 26, no. 6, pp. 1–15, 2012.
- [19] H. A. M.A.B.Sidik, “On the Study of Modernized Lightning Air Terminal,” *Int. Revies Electr. Engineering*, vol. 3, no. 1, pp. 3–8, 2008.
- [20] P. Hasse, *On the studu of Vervoltage of low voltage system*, 2nd ed. IET, 2000.
- [21] R. L. Holle, “Annual Rates of Lightning Fatalities by Country,” in *International Lightning Detection Conference*, 2008, no. January 2008, pp. 1–14.
- [22] Z. A. Hartono and I. Robiah, “A review of Studies on Early Streamer

- Emission and Charge Transfer System conducted in Malaysia .,” in *International Symposium on electromanetic compatibility*, 2006, pp. 128–131.
- [23] Z. A. Hartono and I. Robiah, “The ESE and CVM Lightning Air Terminals : A 25 Year Photographic Record of Chronic Failures,” in *Asia-Pacific International Conference on Lightning (APL)*, 2017, pp. 1–6.
- [24] W. Lu *et al.*, “Two Basic Leader Connection Scenarios Observed in Negative Lightning Attachment Process,” *High Volt.*, vol. 1, no. 1, pp. 11–17, 2016.
- [25] R. Hartono Zainal Abidin, Ibrahim, “Conventional and Un-Conventional Lightning Air Terminals : An Overview,” 2004, pp. 1–39.
- [26] M. Becerra, “Corona Discharges and their Effect on Lightning Attachment Revisited : Upward Leader Initiation and Downward Leader Interception,” *Atmos. Res.*, vol. 149, pp. 316–323, 2014.
- [27] Z. A. Hartono and I. Robiah, “Location Factor and its Impact on Antennae Safety With Reference to Direct Lightning Strikes .,” in *TENCON*, 2000, pp. 1–6.
- [28] N. L. Aleksandrov, E. M. Bazelyan, and Y. P. Raizer, “Initiation and Development of First Lightning Leader : The effects of Coronae and Position of Lightning Origin,” *Atmos. Res.*, vol. 76, no. 1, pp. 307–329, 2005.
- [29] M. Hatfield *et al.*, “A Case Study on Lightning Protection , Building,” *IEEE Trans. Electromagn. Compat.*, vol. 53, no. 3, pp. 849–853, 2011.
- [30] H. Ahmad, “Advanced Laboratory Scale Model of High Phase Conversion Power Transmission Line,” in *IEEE International conference on power and energy*, 2008, no. PECon 08, pp. 822–827.
- [31] M. R. M. E. and F. K. C. H.Ahmad, “Dispersion of Standard and Non Standard Lightning Current to Ground in a Telecommunication Building,” in *The 8th international Power Engineering Conference*, 2007, pp. 207–212.
- [32] N. B. Muhammad Abu Bakar Sidik, Nuru Saniyyati Che Mohd Shukri, Hussein Ahmad, Zolkafli Buntat, “Atmospheric Electric Field Data Logger System,” *J. Teknol.*, vol. 64, no. 4, pp. 119–123, 2013.
- [33] H. Ahmad, S. Member, and L. M. Ong, “An Account of A Modified Lightning Protection System For Power Stations .,” in *IEEE International conference on power and energy*, 2005, pp. 1–5.
- [34] H. Ahmad, Z. A. Malek, N. A. Ahmad, Z. Adzis, N. A. Samad, and M. A. B. Sidik, “On the Concern of Aged Lightning Air Terminal’s Capturing

- Capability and Improvement by Mean of Chemical Treatment,” in *Asia-Pacific International Conference on Lightning*, 2011, pp. 254–257.
- [35] Z. Nawawi, H. Ahmad, M. Abu, B. Sidik, and L. P. Hung, “Lightning Air Terminal Collection Volume Assessment : A New Technique and Device,” *TELKOMNIKA*, vol. 13, no. 1, pp. 13–20, 2015.
- [36] Z. . H. and I.Robiah, “The Minaret Incidents at Putrajaya,” 2010.
- [37] A. M. Hussein and S. Kazazi, “Characteristics of a Tall-Structure Severe Lightning Storm,” *International Symposium on Lightning Protection, SIPDA*, 2013, pp. 102–107.
- [38] F.Heilder, “Self-Initiated and Other-Triggered Positive Upward Lightning Measured at the Peissenberg Tower ,” *International Conference on Lightning Protection (ICLP)*, 2014, pp. 157–166.
- [39] C. Gomes, “Concerns of the Application of Lightning Protection Risk Assesment for Small Structures,” *International Conference on Lightning Protection (ICLP)*, 2016, pp. 1–5.
- [40] S. Jacob, “Lightning Protection of a Temporary Structure in Open Area,” in *International Conference on lightning protection*, 2016, pp. 1–5.
- [41] M. Doljinsuren and C. Gomes, “Lightning incidents in Mongolia,” *Geomatics, Natural Hazards and Risk*, 2017, vol. 6, no. 8, pp. 686–701.
- [42] K. Filik, G. Karnas, P. Szczupak, G. Maslowski, and R. Ziemba, “Experimental Investigation of the Effectiveness of Lightning Protection System,” *Selected issues of Electrical Engineering and Electronics (WZEE)*, 2016, no. 8, pp. 1–6.
- [43] J. L. Bermudez, F. Rachidi, A. Chisholm, M. Rubinstein, M. Hussein, and S. Chang, “On the Use of Transmission Line Theory to Represent a Nonuniform Vertically-Extended Object Struck by Lightning,” *IEEE International Symposium on Electromagnetic Compatibility*, 2003, pp. 501–504.
- [44] E. P. Nicolopoulou, I. F. Gonos, and I. A. Stathopoulos, “Experimental Investigation of the External Lightning Protection of Ships Through Impulse Voltage Tests on a Scaled-Down Ship Model,” *IET Sci. Meas. Technol.*, vol. 10, no. 8, pp. 855–865, 2016.
- [45] M. Z. a. Ab Kadir, N. R. Misbah, C. Gomes, J. Jasni, W. F. Wan Ahmad, and M. K. Hassan, “Recent Statistics on Lightning Fatalities in Malaysia,” *2012 International Conference on Lightning Protection (ICLP)*, 2012, pp. 1–5.

- [46] K. P. Naccarato, "How Ground Flash Density Obtained by Lightning Location Network can be Used in Lightning Protection Standards: A Case Study in Brazil," *19th international lightning detection conference*, 2006, pp. 5–7.
- [47] H. J. Christian *et al.*, "Global Frequency and Distribution of Lightning as Observed from Space by the Optical Transient Detector," *J. Geogr. Res.*, vol. 108, no. 10, pp. 1–15, 2003.
- [48] R. B. Anderson, "Investigating a Possible New Pathway of Current to Determine the Cause of Injuries Related to Close Lightning Flashes," *IEEE Eng. Med. Biol. Mag.*, vol. 19, no. 1, pp. 105–113, 2001.
- [49] Department for Communities and Local Government, "Fire Statistics in United Kingdom," 2008.
- [50] M. Ahrens, "Lightning Fires and Lightning strikes," 2008.
- [51] D. M. Elsom and J. D. C. Webb, "Deaths and injuries from lightning in the UK, 1988 – 2012," *Weather*, vol. 69, no. 8, pp. 221–226, 2013.
- [52] D. M. Elsom, "Deaths and Injuries Caused by Lightning in the United Kingdom: analyses of two databases," *Appl. Mech. Mater.*, vol. 56, no. 6, pp. 325–334, 2001.
- [53] X. I. E. Yiran, W. U. Jian, Z. Tengfei, and L. I. U. Xuetao, "Cloud-to-Ground Lightning Activity in a Hailstorm Over the Central Lower Latitude Plateau of China," in *international conference on lightning protection system (ICLP)*, 2014, pp. 1358–1360.
- [54] Y. Zhang, W. Zhang, and Q. Meng, "Lightning Casualties and Damages in China from 1997 to 2010," *International conference on lightning protection system (ICLP)*, 2012, pp. 6–10.
- [55] F. T. Illiyas, K. Mohan, S. K. Mani, and A. P. Pradeepkumar, "Lightning Risk in India," 2014.
- [56] C. Gomes, M. Ahmed, F. Hussain, and K. R. Abeyasinghe, "Lightning Accidents and Awareness in South Asia: Experience in Sri Lanka and Bangladesh," in *International conference on lightning protection system (ICLP)*, 2006, pp. 1–4.
- [57] W. M. Dlamini, "Lightning Fatalities in Swaziland: 2000–2007," *Nat. Hazards*, vol. 50, no. 1, pp. 179–191, Dec. 2009.
- [58] G. D. Peppas, "Analysis of Lightning Impacts in Greece," *International conference on lightning protection system (ICLP)*, 2012, pp. 2007–2011.

- [59] N. A. Ahmad, N. Najihah, A. Bakar, and Z. Adzis, "Study of Lightning Fatalities in Malaysia from 2004 to 2012," *J. Teknol.*, vol. 1, no. 6, pp. 9–13, 2014.
- [60] R. L. Holle, "Some Aspects of Global Lightning Impacts," *International conference on lightning protection system (ICLP)*, 2014, pp. 1390–1395.
- [61] C.B.Moore, "Lightning Rod Improvement Studies," *J. Appl. Meteorol.*, vol. 39, no. 3, pp. 593–609, 2000.
- [62] C.B.Moore, "The Case for Using Blunt-Tipped Lightning Rods as Strike Receptors," *J. Appl. Meteorol.*, vol. 42, no. 1, pp. 984–993, 2003.
- [63] W. Rison, "Experimental Validation of Conventional and Non-Conventional Lightning Protection," *Power Engineering Society General Meeting*, 2003, vol. 87801, pp. 2195–2200.
- [64] M. Akyuz and V. Cooray, "The Franklin Lightning Conductor : Conditions Necessary for the Initiation of a Connecting Leader," *J. Electrostat.*, vol. 52, no. 4, pp. 319–325, 2001.
- [65] F. D'Alessandro, "Striking distance Factors and Practical Lightning Rod Installations: a Quantitative Study," *J. Electrostat.*, vol. 59, no. 1, pp. 25–41, Jul. 2003.
- [66] A. Kern, C. Schelthoff, and M. Mathieu, "Probability of Lightning Strikes to Air-Terminations of Structures Using the Electro-Geometrical Model Theory and the Statistics of Lightning Current Parameters," *Atmos. Res.*, vol. 117, no. 1, pp. 2–11, Nov. 2011.
- [67] Z. A. Hartono, "Air Terminal Placement : The Key to An Effective Lightning Protection of Structures," 2015.
- [68] A. Srivastava and M. Mishra, "Positioning of Lightning Rods Using Monte Carlo technique," *J. Electrostat.*, vol. 76, no. 3, pp. 201–207, Aug. 2015.
- [69] F. D. Alessandro and J. R. Gumley, "A Collection Volume Method a for the Placement of Air Terminals for the Protection of Structures Against Lightning," *J. Electrostat.*, vol. 50, pp. 279–302, 2001.
- [70] F. D. Alessandro, "The use of ' Field Intensification Factors ' in Calculations for Lightning Protection of Structures," *J. Electrostat.*, vol. 58, no. 6, pp. 17–43, 2003.
- [71] V. Shostak, T. Petrenko, W. Janischewskyj, and F. Rachidi, "Electric Field Within Lightning Protection Volume in presence of a Descending Leader,"

- Electr. Power Syst. Res.*, vol. 85, no. 3, pp. 82–89, Apr. 2012.
- [72] Y. K. Chung, K. S. Lee, and B. H. Lee, “Analysis and Test on Electric Field Concentration Effect of Bipolar Conventional Air Terminal,” *2014 International Conference on Lightning Protection, ICLP*, pp. 1545–1548.
- [73] B. Vahidi and S. S. Farokhi, “Electromagnetic Field Inside the Building Due to Lightning Stroke,” *International multif topic conference (INMIC)*, 2005, no. 1, pp. 1–5.
- [74] R. Liu, Y. Wang, Z. Zhao, and Y. Zhang, “Magnetic Field Distribution Inside Metallic Grid-like Buildings Struck by Lightning Based on Finite Element Method,” *international conference on lightning protection system (ICLP)*, 2014, pp. 1712–1715.
- [75] M. S. Vieira and J. M. Janiszewski, “Propagation of Lightning Electromagnetic Fields in the Presence of Buildings,” *Electr. Power Syst. Res.*, vol. 118, no. 4, pp. 101–109, Jan. 2015.
- [76] E. Bachelier, F. Issac, and D. Prost, “Protection Against Lightning of Reinforced Concrete Buildings,” *International conference on lightning protection system (ICLP)*, 2014, pp. 735–740.
- [77] H. Zhou, G. Diendorfer, R. Thottappillil, H. Pichler, and M. Mair, “Measured Current and Close Electric Field Changes Associated with the Initiation of Upward Lightning from a Tall Tower,” *J. Geogr. Res. Atmos.*, vol. 117, no. 2, pp. 1–9, 2012.
- [78] P. N. Mikropoulos and T. E. Tsovilis, “Interception Probability and Shielding Against Lightning,” *IEEE Transation Power Deliv.*, vol. 24, no. 2, pp. 863–873, 2009.
- [79] A. Smorgonskiy, A. Tajalli, F. Rachidi, M. Rubinstein, G. Diendorfer, and H. Pichler, “Analysis of Lightning Events Preceding Upward Flashes from Gaisberg and Santis Towers,” *2014 International Conference on Lightning Protection, ICLP 2014*, 2014, pp. 1382–1385.
- [80] M. Miki *et al.*, “Initial Stage in Lightning Initiated from Tall Objects and in Rocket- Triggered Lightning,” *J. Geophys. Res.*, vol. 110, no. 1, pp. 1–15, 2005.
- [81] M. Rezinkina, O. Rezinkin, F. D. Alessandro, A. Danyliuk, A. Guchenko, and S. Lytvynenko, “Experimental and Modelling Study of the Dependence of Corona Discharge on Electrode Geometry and Ambient Electric field,” *J.*

- Electrostat.*, vol. 87, no. 1, pp. 79–85, 2017.
- [82] W. Lu and L. Chen, “Lightning Attachment Process Involving Connection of the Downward Negative Leader to the Lateral Surface,” *Geophys. Res. Lett.*, vol. 40, no. 4, pp. 5531–5535, 2013.
- [83] G. Berger, L. Gallin, and S. Ait-amar, “Occurrence of New Upward Positive Leaders Triggered by Negative Downward CG lightning,” *international conference on high voltage engineering and application*, 2010, pp. 112–115.
- [84] A. Kern, C. Schelthoff, and M. Mathieu, “Calculation of Interception Efficiencies for Air- Terminations Using a Dynamic Electro-Geometrical Model,” in *International symposium on lightning protection*, 2011, pp. 25–30.
- [85] T. D. Farkas, N. Szedenik, and I. Kiss, “Sensitivity analysis in lightning protection risk management,” *J. Electrostat.*, vol. 71, no. 3, pp. 582–585, Jun. 2013.
- [86] Irshad Ullah.MNR Baharom, H.Ahamd, H.M.Luqman, “Lightning Strike Probabilty on Macro Geometrical Structures,” *IEEE International Conference on Power and Energy (PECon)*, 2016, pp. 290–294.
- [87] Y. Beck, “3d Lightning Strikes Probability Program,” *Electrical and Electronics Engineering*, 2008, pp. 368–372.
- [88] T. Gammon *et al.*, “‘ Arc Flash ’ Hazards , Incident Energy , PPE Ratings , and Thermal Burn Injury — A Deeper Look,” *IEEE Trans. Ind. Appl.*, vol. 51, no. 5, pp. 4275–4283, 2015.
- [89] R. S. Leroy, “Hazard or Risk Analysis, Overcoming the Human Factor,” 2015, pp. 1–6.
- [90] B. Suhardi, “Analysis of Potential Work Accidents Using Hazard Identification , Risk Assessment and Risk Control (HIRARC) Method,” *International Conference of Industrial, Mechanical, Electrical, Chemical Engineering (ICIMECE)*, 2016, pp. 196–200.
- [91] A. M. Saedi, J. J. Thambirajah, and A. Pariatamby, “A HIRARC Model for Safety and Risk Evaluation at a Hydroelectric Power Generation Plant,” *Saf. Sci.*, vol. 70, no. 3, pp. 308–315, 2014.
- [92] Z. A. Hartono and R. Ibrahim, “A Database of Lightning Damage Caused by Bypasses of Air Terminals on Buildings in Kuala Lumpur, Malaysia,” *International Symposium on Lightning Protection*, 2001, no. February, pp. 211–216.

- [93] F. D'Alessandro and N. I. Petrov, "Field study on the interception efficiency of lightning protection systems and comparison with models," in *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 2006, pp. 1365–1386.
- [94] G. S. Ait Amar and Berger, "A Model of Protection of Earthed Structures by Means of Lightning Rod Conductors," *Poewer technology*, 2005, pp. 1–6.
- [95] "NFPA Standard for the Istallation Lightning Protection System," 2006.
- [96] "BS EN / IEC 62305 Lightning protection standard," 2008.
- [97] "Malaysian standard BS 6325-1 High Voltage and Lightning Protection," 1999.
- [98] M. Nassereddine and A. Hellany, "Designing a Lightning Protection System Using the Rolling Sphere Method," *International Conference on Computer and Electrical Engineering*, 2009, pp. 502–506.
- [99] S. E. Silva Artigas, "The Ionizing Surfaces method: An alternative approach for lightning protection design," *International Symposium on Lightning Protection (XII SIPDA)*, 2013, pp. 304–308.
- [100] M. K. Hassan, R. Z. A. Rahman, A. C. H. E. Soh, and M. Z. A. A. B. Kadir, "Lightning Strike Mapping for Peninsular Malaysia Using Artificial Itelligence Techniques," *J. Theor. Appl. Inf. Technol.*, vol. 34, no. 2, pp. 202–214, 2011.
- [101] M. K. Sanders, "NFPA 780 Standard for the Installation of Lightning Protection Systems 2011 Edition," 2011.
- [102] V. Heller, "Scale effects in Physical Hydraulic Engineering Models," *J. Hydraul. Res.*, vol. 49, no. 3, pp. 293–306, Jun. 2011.
- [103] M. N. Partl, Alvaro Garcia, Pietro Lura and I. J. Jerjen, "Influence of Cement Content and Environmental Humidity on Asphalt Emulsion and Cement Composites Performance," *Mater. Struct.*, vol. 12, no. 4, pp. 1–15, 2012.
- [104] D. Smyl, M. Hallaji, A. Seppänen, and M. Pour-ghaz, "Quantitative Electrical Imaging of Three-Dimensional Moisture Flow in Cement-Based Materials," *Int. J. Heat Mass Transf.*, vol. 103, no. 3, pp. 1348–1358, 2016.
- [105] M. Khalifa, *High Voltage Engineering Theory and Practice*, 1st ed. New York: Marceln Dekker, 1990.
- [106] E. Kuffel, *High Voltage Engineering*, Second. Wobuen: Butterworth-Heinemann, 2000.

- [107] Z. A. Hartono and I. Robiah, “A Study of Non-Conventional Air Terminals and Stricken Points in a High Thunderstorm Region,” *Lightning Protection (ICLP), 2000 International Conference on*, 2000, no. April, pp. 357–361.
- [108] Z. A. Hartono and I. Robiah, “Close Proximity Bypasses to Collection Volume and Early Streamer Emission Air Terminals,” in *7th Asia-Pacific International Conference on Lightning*, , Chengdu, China, 2011, pp. 863–867.
- [109] V. Cooray, *Lightning Physics and Lightning Protection*, 1st ed. London: Nicki Dennis, 2009.



PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH